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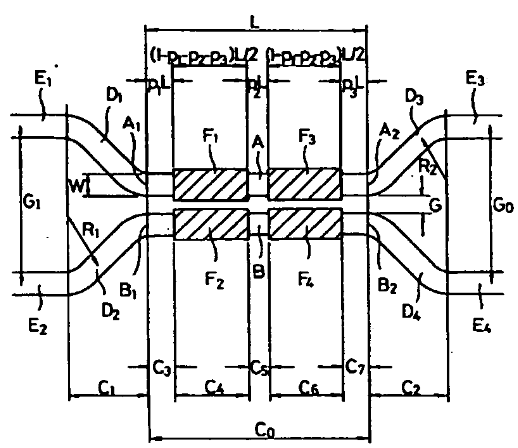
(54) Directional coupler type optical function element.

(57) Provided is a directional coupler type optical function element with high extinction ratio, in which a junction of a 2-input/2-output directional coupler or 1-input/2-output directional coupler, formed of a semiconductor or dielectric, is formed by successively optically connecting, from the input side to the output side, a front-stage partial junction (C_3), front-stage partial junction (C_4) with electrode (F_1, F_2), central partial junction (C_5), rear-stage partial junction (C_6) with electrode (F_3, F_4), and rear-stage partial junction (C_7), each having a predetermined length.

The connection state at the front-stage partial junction (C_3) and an incidence-side lead section (C_1) optically connected thereto and the connection state at the rear-stage partial junction (C_7) and an emergence-side lead section (C_2) optically connected thereto cancel each other, thereby equivalently providing a symmetrical connection state and preventing the extinction ratio for a cross mode from lowering. By forming the central partial junction (C_5) with a proper length, moreover, the extinction ratio for a through mode can be kept high enough. Thus, high extinction ratio characteristics can be enjoyed for either the cross or through modes.

FIG. 3



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The present invention relates to a directional coupler type optical function element of a novel construction, and more particularly, to a directional coupler type optical function element having very high extinction ratio characteristics and adapted for use as an optical switch, polarizing splitter, optical modulator, wavelength division multiplexer/demultiplexer, etc.

Recently, various optical function elements having a directional coupler of a waveguide type have been developed, and optical switches, polarizing splitters, optical modulators, wavelength division multiplexer/demultiplexers, etc. using these elements have been proposed.

Figs. 1 and 2 show examples of conventional optical function elements of a directional coupler type. The element shown in Fig. 1 is a 2-input/2-output element, while the element shown in Fig. 2 is a 1-input/2-output element.

In Fig. 1, a junction C_0 of a length L is formed by arranging two optical waveguides A and B of equal widths W close to each other in parallel relation, with a distance G for evanescent connection between them.

Curved optical waveguides D_1, D_2, D_3 and D_4 with a path width W and curvature radius R are optically connected to the respective incidence ends A_1 and B_1 and emergence ends A_2 and B_2 of the optical waveguides A and B of the junction C_0, respectively, thus forming incidence-side lead section C_1 and emergence-side lead section C_2. Also, straight optical waveguides E_1, E_2, E_3 and E_4 with the path width W are optically connected to the curved optical waveguides D_1, D_2, D_3 and D_4, respectively, with a distance G_0 between the respective path-width centers of the waveguides E_1 and E_2 and between those of the waveguides E_3 and E_4. Electrodes F_1, F_2, F_3 and F_4 are mounted on the optical waveguides A and B of the junction C_0 so that electrical signals can be introduced from the electrodes into the waveguides. The distances between the electrodes F_1 and F_3 and between the electrodes F_2 and F_4 are substantially zero.

If the straight optical waveguide E_1 is an incidence port, the straight optical waveguides E_3 and E_4 serve as a through port and a cross port, respectively.

The 1-input/2-output element of Fig. 2 is a modified version of the 2-input/2-output element of Fig. 1, in which one straight optical waveguide E_0 is optically connected to only the incidence end A_1 of the optical waveguide A in a direct manner. In this element, the straight optical waveguide E_0 is an incidence port, and the straight optical waveguides E_3 and E_4 serve as a through port and a cross port, respectively.

In order to incorporate these elements in a fiber communication system, which is going to be practically used, it is necessary to prevent errors attributable to cross talk. Thus, the elements are expected to be subject to less cross talk, that is, to have high extinction ratio characteristics.

In the case of the element shown in Fig. 1, a theoretically perfect cross mode is established to heighten the extinction ratio without limitation by applying proper electrical signals from the electrodes F_1, F_2, F_3 and F_4. Connections at the incidence- and emergence-side lead sections C_1 and C_2 cannot, however, provide a perfect through mode, and in this case, the theoretical value of the extinction ratio ranges from about 20 to 30 dB at the highest.

In the case of the element shown in Fig. 2, moreover, the extinction ratio for the through mode can be made about 10 dB higher than that of the element shown in Fig. 1. For the cross mode, however, the extinction ratio ranges from only about 10 to 20 dB.

Thus, the conventional elements, which have a low extinction ratio for the through or cross mode, cannot exhibit high extinction ratio characteristics for both the through and cross modes.

The extinction ratio used here is a value given by the followed equation: $10\log_{10}(|r|^2/|s|^2)$, where $|r|^2$ is the output power of the through port, and $|s|^2$ is the output power of the cross port.

Among optical function elements constructed in this manner, known examples of those which have relatively high extinction ratio characteristics include an optical switch with an extinction ratio of about 27 dB reported in Technical Digest Integrated and Guide-wave Optics '86 by P. Granestrand et al. and a polarizing splitter with an extinction ratio of about 28 dB reported in the 1990 Autumn National Meeting C-216 of the Institute of Electronic Intelligence and Communication Engineers of Japan by H.M. Mak et al.

Meanwhile, those optical function elements which are practically used in an optical communication system are expected to have an extinction ratio of 15 dB or more.

To meet this requirement, intense studies have been made of the causes of low extinction ratios of directional coupler type optical function elements.

Among these studies, there is one whose results are described in Institution of Electrical and Electronics Engineers Journal (IEEE. J.) of Quantum Electronics (Vol. 24, March, 1988) by Jean-Pierre Weber et al. This description indicates that the low extinction ratio is attributable to difficulty in refractive index control of the directional coupler for a required switching state.

L. McCanghan et al. also reported in IEEE. J. of Quantum Electronics (Vol. QE-22, No. 6, June, 1986) that the low extinction ratio is attributable to the irregularity of the refractive index of optical waveguides with respect to the extending direction thereof (direction of light propagation).

Further, T.K. Findakly et al. indicated the following in Journal of Lightwave Technology (Vol. 6, No. 1, January, 1988). According to this report, the extinc-

tion ratio is inevitably lowered because in a through mode there exist small connections at incidence- and emergence-side lead sections for connecting optical fibers.

Among the three causes described in these reports, the one reported by Jean-Pierre Weber et al can be removed by properly selecting the method of driving the element and the material of the optical waveguides. Further, the cause reported by L. McCanghan et al. can be removed by improving film growth control during the formation of the optical waveguides.

The cause indicated by T.K. Findakly et al., however, is an unavoidable problem which cannot be solved unless the outside diameter of the optical fiber to be connected is reduced to several micrometers so that the element requires no lead sections.

In the case of the optical function element of the conventional construction shown in Fig. 1, the extinction ratio is lowered only for the through mode due to the connections at the incidence- and emergence-side lead sections C_1 and C_2 even though the element is a perfectly symmetrical directional coupler.

The extinction ratio characteristics of the optical function element depend on the lower one of the extinction ratios for the through and cross modes. Even in case the extinction ratio for the cross mode is unlimited, therefore, the whole element can enjoy only a low extinction ratio if that for the through mode is low.

In the case of the optical function element shown in Fig. 1, moreover, the extinction ratio for the cross mode can be also lowered if the incidence- and emergence-side lead sections C_1 and C_2 do not have the same configuration.

In many of practical versions of the element of Fig. 1, for example, the radius of curvature of the incidence-side lead section C_1 is different from that of the emergence-side lead section C_2, so that these sections are not symmetrical. In such a case, the extinction ratio for the cross mode, as well as that for the through mode, is lowered for the aforesaid reason.

Thus, in the conventional directional coupler type optical function elements, the extinction ratio for the through mode is low, and that for the cross mode is also lowered if the incidence- and emergence-side lead sections C_1 and C_2 are not symmetrical.

The object of the present invention is to provide a directional coupler type optical function element of a novel construction capable of exhibiting an extinction ratio of 30 dB or more for either of through and cross modes.

In order to achieve the above object, according to the present invention, there is provided a directional coupler type optical function element which comprises: a directional coupler including a junction of a length L having two parallel optical waveguides of equal widths formed of a material exhibiting an electrooptical effect or a material capable of refractive index control by means of an electrical signal; at least one optical waveguide optically connected to the incidence end of one of the optical waveguides of the junction; and curved or straight optical waveguides connected individually to the respective emergence ends of the two optical waveguides of the junction, the junction including a front-stage partial junction of a length $p_1 \times L$, a front-stage partial junction with electrode of a length $(1 - p_1 - p_2 - p_3) \times L/2$, a central partial junction of a length $p_2 \times L$, a rear-stage partial junction with electrode of the same length as that of the front-stage partial junction with electrode, and a rear-stage partial junction of a length $p_3 \times L$, p_1, p_2 and p_3 being decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_2 \neq 0$ or $p_1, p_2 \neq 0$).

In one embodiment, there is provided a 2-input/2-output directional coupler type optical function element which comprises a directional coupler including a junction of a length L having two parallel optical waveguides of equal widths formed of a material exhibiting an electrooptical effect or a material capable of refractive index control by means of an electrical signal, the respective incidence ends of the two optical waveguides of the junction being optically connected to curved or straight optical waveguides, individually, thereby forming an incidence-side lead section, the respective emergence ends of the two optical waveguides of the junction being optically connected to curved or straight optical waveguides, individually, thereby forming an emergence-side lead section, the junction including a front-stage partial junction of a length $p_1 \times L$, a front-stage partial junction with electrode of a length $(1 - p_1 - p_2 - p_3) \times L/2$, a central partial junction of a length $p_2 \times L$, a rear-stage partial junction with electrode of the same length as that of the front-stage partial junction with electrode, and a rear-stage partial junction of a length $p_3 \times L$, where p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_2 \neq 0$). Alternatively, one embodiment provides a 1-input/2-output directional coupler type optical function element which comprises a directional coupler including a junction of a length L having two parallel optical waveguides of equal widths formed of a material exhibiting an electrooptical effect or a material capable of refractive index control by means of an electrical signal, only one of the two optical waveguides of the junction being optically connected at the incidence end thereof with a straight optical waveguide, the respective emergence ends of the two optical waveguides of the junction being optically connected to curved or straight optical wavegui- des, individually, thereby forming an emergence-side lead section, the junction including a front-stage partial junction of a length $p_1 \times L$, a front-stage partial junction with electrode of a length $(1 - p_1 - p_2 - p_3) \times L/2$, a central partial junction of a length $p_2 \times L$, a rear-stage partial junction with electrode of the same length as that of the front-stage partial junction with electrode, and

a rear-stage partial junction of a length $p_3 \times L$, where p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_1, p_2 \neq 0$).

There will now be described, by way of example only, preferred embodiments of the invention, with reference to the accompanying drawings, in which:

Fig. 1 is a plane pattern diagram showing a configuration of a conventional 2-input/2-output directional coupler;

Fig. 2 is a plane pattern diagram showing a configuration of a conventional 1-input/2-output directional coupler;

Fig. 3 is a plane pattern diagram showing the basic configuration of a 2-input/2-output directional coupler type optical function element according to the present invention;

Fig. 4 is a plane pattern diagram showing an example of connection of electrodes mounted on a junction of the optical function element of Fig. 3 whose optical waveguides are formed of a semiconductor material;

Fig. 5 is a plane pattern diagram showing an example of connection of electrodes mounted on a junction of the optical function element of Fig. 3 whose optical waveguides are formed of a dielectric material;

Fig. 6 is a plane pattern diagram showing another example of connection of electrodes mounted on the junction of the optical function element of Fig. 3 whose optical waveguides are formed of a dielectric material;

Fig. 7 is a plane pattern diagram showing the basic configuration of a 1-input/2-output directional coupler type optical function element according to the present invention;

Fig. 8 is a plane pattern diagram showing an example of connection of electrodes mounted on a junction of the optical function element of Fig. 7 whose optical waveguides are formed of a semiconductor material;

Fig. 9 is a plane pattern diagram showing an example of connection of electrodes mounted on a junction of the optical function element of Fig. 7 whose optical waveguides are formed of a dielectric material;

Fig. 10 is a plane pattern diagram showing another example of connection of electrodes mounted on the junction of the optical function element of Fig. 7 whose optical waveguides are formed of a dielectric material;

Fig. 11 is a plane pattern diagram showing a 2-input/2-output directional coupler type optical function element according to Embodiment 1 or 2;

Fig. 12 is a sectional view taken along line XII-XII of Fig. 11;

Fig. 13 is a sectional view taken along line XIII-XIII of Fig. 11;

Fig. 14 shows a theoretical characteristic curve representing the switching characteristic of the optical function element of Embodiment 1;

Fig. 15 is a graph showing the relationship between the extinction ratio and value p_2 of the optical function element of Embodiment 1;

Fig. 16 shows a theoretical characteristic curve representing the switching characteristic of the optical function element of Embodiment 2;

Fig. 17 is a graph showing the relationship between the extinction ratio and value p_2 of the optical function element of Embodiment 2;

Fig. 18 is a plane pattern diagram showing a 1-input/2-output directional coupler type optical function element according to Embodiment 3 or 4;

Fig. 19 shows a theoretical characteristic curve representing the switching characteristic of the optical function element of Embodiment 3;

Fig. 20 is a graph showing the relationship between the extinction ratio and value p_2 of the optical function element of Embodiment 3;

Fig. 21 is a graph showing the theoretical relationship between the extinction ratio and value p_1 of the optical function element of Embodiment 3 observed where $p_2 = p_3 = 0$ is given;

Fig. 22 shows a theoretical characteristic curve representing the switching characteristic of the optical function element of Embodiment 4; and

Fig. 23 is a graph showing the relationship between the extinction ratio and value p_2 of the optical function element of Embodiment 4.

Fig. 3 is a plane pattern diagram showing the basic configuration of a 2-input/2-output directional coupler type optical function element according to an embodiment of the present invention. As seen from Fig. 3, a plane pattern of the optical function element differs from the conventional 2-input/2-output directional coupler type optical function element shown in Fig. 1 only in that a junction Co is constructed as follows.

First, two optical waveguides A and B with the same width (path width W) are arranged parallel to each other with a fine space G between them at the junction C_0, and curved optical waveguides D_1 and D_2 with a curvature radius R_1 and a path width W are optically connected to incidence ends A_1 and B_1 of the waveguides A and B, respectively, thus constituting an incidence-side lead section C_1. Likewise, curved optical waveguides D_3 and D_4 with a curvature radius R_2 and the path width W are optically connected to emergence ends A_2 and B_2 of the waveguides A and B, respectively, thus constituting an emergence-side lead section C_2. At the incidence-side lead section C_1, moreover, straight optical waveguides E_1 and E_2 with the path width W are optically connected to the curved optical waveguides D_1 and D_2, respectively, so that the distance between the respective centers of the waveguides E_1 and E_2 is G_1. At the emergence-side lead section C_2, on the other hand, straight optical

waveguides E_3 and E_4 with the path width W are optically connected to the curved optical waveguides D_3 and D_4, respectively, so that the distance between the respective centers of the waveguides E_3 and E_4 is G_0. If the straight optical waveguide E_1 is an incidence port, the straight optical waveguides E_3 and E_4 serve as a through port and a cross port, respectively.

The incidence- and emergence-side lead sections C_1 and C_2 are not limited to the illustrated arrangement including the curved optical waveguides. Alternatively, for example, the incidence end A_1 and the straight optical waveguide E_1, the incidence end B_1 and the straight optical waveguide E_2, the emergence end A_2 and the straight optical waveguide E_3, and the emergence end B_2 and the straight optical waveguide E_4 may be optically connected to one another by means of finely tapered straight optical waveguides, individually.

Any of these optical waveguides is formed of a material which generates an electrooptical effect or a material of a structure such that its refractive index can be controlled by means of an electrical signal. For example, each optical waveguide may be a multilayer laminate structure of a semiconductive material, such as GaAs/AlGaAs, formed by the MOCVD method.

The junction C_0 is formed by optically connecting a front-stage partial junction C_3, front-stage partial junction C_4 with electrode, central partial junction C_5, rear-stage partial junction C_6 with electrode, and rear-stage partial junction C_7, in the order named, ranging from the incidence ends A_1 and B_1 to the emergence ends A_2 and B_2 thereof.

If the overall length of the junction C_0 is L, and if p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_2 \neq 0$), the length of the front-stage partial junction C_3 is $p_1 \times L$, that of the front-stage partial junction C_4 with electrode is $(1 - p_1 - p_2 - p_3) \times L/2$, that of the central partial junction C_5 is $p_2 \times L$, that of the rear-stage partial junction C_6 with electrode is $(1 - p_1 - p_2 - p_3) \times L/2$, and that of the rear-stage partial junction C_7 is $p_3 \times L$.

In this case, the combination of the incidence-side lead section C_1 and the front-stage partial junction C_3 newly constitutes an equivalent incidence-side lead section $(C_1 + C_3)$, while the combination of the emergence-side lead section C_2 and the rear-stage partial junction C_7 newly constitutes an equivalent emergence-side lead section $(C_2 + C_7)$. Thus, the coefficients p_1 and p_3 are selected as values which determine the respective lengths of the front- and rear-stage partial junctions C_3 and C_7 in a manner such that the connection (or coupling effect) at the combination of the incidence-side lead section C_1 and the front-stage partial junction C_3 is similar to the connection (or coupling effect) at the combination of the emergence-side lead section C_2 and the rear-stage partial junction C_7, so that the element can enjoy a perfectly symmetrical connection state as a whole for the entire equivalent incidence-and emergence-side lead sections.

The coefficient p_2 is selected as a value such that the coupling effect of the central partial junction C_5 is equal to the sum of the coupling effect of $(C_1 + C_3)$ and $(C_2 + C_7)$. That is the central partial junction C_5 has a length corresponding to a maximum value of the extinction ratio as measured in a through mode with the length of the junction C_5 varied.

The states of connection between electrodes F_1, F_2, F_3 and F_4 at the partial junctions C_4 and C_6 vary depending on the optical waveguide material used. If the waveguide material is a semiconductor, for example, it is necessary only to provide an inverted $\Delta\beta$ structure such that the electrodes F_2 and F_3 and the electrodes F_1 and F_4 are connected by means of leads f_1 and f_2, respectively, as shown in Fig. 4. If the waveguide material is a dielectric, such as $LiNbO_3$, it is necessary only to make connections corresponding to the crystalline orientation of the dielectric, as shown in Figs. 5 and 6.

In the optical function element of the embodiment, the equivalent incidence-side lead section $(C_1 + C_3)$, formed of the incidence-side lead section C_1 and the front-stage partial junction C_3, and the equivalent emergence-side lead section $(C_2 + C_7)$, formed of the emergence-side lead section C_2 and the rear-stage partial junction C_7, serve that the coupling effect of section $(C_2 + C_7)$ equals the coupling effect of section $(C_1 + C_3)$. In the element as a whole, therefore, the front-stage partial junction C_4 with electrode, central partial junction C_5, and rear-stage partial junction C_6 with electrode develop a state equivalent to the one obtained in the case where the incidence- and emergence-side lead sections are perfectly symmetrical. Thus, the extinction ratio for a cross mode can be prevented from lowering.

The central partial junction C_5 formed in the junction C_0 is adjusted to a length such that the extinction ratio has a maximum in the through mode, that is, a connection (or coupling effect) equivalent to the connection (or coupling effect) at the combination of the incidence- and emergence-side lead sections C_1 and C_2 and the partial junctions C_3 and C_7 can be obtained. In this case, the extinction ratio for the through mode is unlimited theoretically.

Thus, in the optical function element of the embodiment, the extinction ratio for either of the cross and through modes is much higher than in the conventional cases.

Fig. 7 shows the basic configuration of a 1-input/2-output directional coupler type optical function element according to an embodiment of the present invention.

A plane pattern of this optical function element differs from the conventional 1-input/2-output directional coupler type optical function element shown in Fig. 2 only in that a junction C_0 is constructed as follows.

First, two optical waveguides A and B with the

same width (path width W) are arranged parallel to each other with a fine space G between them at the junction C_0, and a straight optical waveguide E_0 with a path width W is optically connected to an incidence end A_1 of the one waveguide A, thus constituting an incidence port. Also, curved optical waveguides D_3 and D_4 with a curvature radius R and the path width W are optically connected to emergence ends A_2 and B_2 of the waveguides A and B, respectively, thus constituting an emergence-side lead section C_2. Moreover, straight optical waveguides E_3 and E_4 with the path width W are optically connected to the curved optical waveguides D_3 and D_4, respectively, so that the distance between the respective path-width centers of the waveguides E_3 and E_4 is G_0, thus constituting a through port (E_3) and a cross port (E_4), respectively.

In the case of this optical function element, as in the case of the element shown in Fig. 3, the emergence-side lead section C_2 is not limited to the illustrated arrangement including the curved optical waveguides. Alternatively, for example, the emergence ends A_2 and B_2 may be optically connected to the straight optical waveguides E_3 and E_4, respectively, by means of finely angled straight optical waveguides.

Any of these optical waveguides, like those of the optical function element shown in Fig. 3, is formed of a material which generates an electrooptical effect or a material of a structure such that its refractive index can be controlled by means of an electrical signal.

As in the case of the optical function element shown in Fig. 3, the junction C_0 is formed by optically connecting a front-stage partial junction C_3, front-stage partial junction C_4 with electrode, central partial junction C_5, rear-stage partial junction C_6 with electrode, and rear-stage partial junction C_7, in the order named, ranging from the incidence end A_1 to the emergence ends A_2 and B_2 thereof.

If the overall length of the junction C_0 is L, and if p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_1, p_2 \neq 0$), the length of the front-stage partial junction C_3 is $p_1 \times L$, that of the front-stage partial junction C_4 with electrode is $(1 - p_1 - p_2 - p_3) \times L/2$, that of the central partial junction C_5 is $p_2 \times L$, that of the rear-stage partial junction C_6 with electrode is $(1 - p_1 - p_2 - p_3) \times L/2$, and that of the rear-stage partial junction C_7 is $p_3 \times L$.

In this case, the coefficients p_1 and p_3 are selected as values such that the connection at the front-stage partial junction C_3 with the length $p_1 \times L$ is similar to the connection at the combination of the rear-stage partial junction C_7 and the emergence-side lead section C_2, so that the whole element,is equivalent to the one obtained in the case where the incidence- and emergence-side lead sections are perfectly symmetrical.

The coefficient p_2 is selected as a value such that the central partial junction C_5 has a length corresponding to a maximum value of the extinction ratio as measured in a through mode with the length of the junction C_5 varied.

The states of connection between electrodes F_1, F_2, F_3 and F_4 at the partial junctions C_4 and C_6 vary depending on the optical waveguide material used. If the waveguide material is a semiconductor, for example, it is necessary only to provide an inverted $\Delta\beta$ structure such that the electrodes F_2 and F_3 and the electrodes F_1 and F_4 are connected by means of leads f_1 and f_2, respectively, as shown in Fig. 8. If the waveguide material is a dielectric, such as $LiNbO_3$, it is necessary only to make connections corresponding to the crystalline orientation of the dielectric, as shown in Figs. 9 and 10.

Also in the case of this 1-input/2-output directional coupler type optical function element, the connection at the front-stage partial junction C_3 is similar to the connection at the combination of the rear-stage partial junction C_7 and the emergence-side lead section C_2. In this directional coupler as a whole, therefore, the front-stage partial junction C_4 with electrode, central partial junction C_5, and rear-stage partial junction C_6 with electrode generate a state equivalent to the one obtained in the case where the incidence- and emergence-side lead sections are perfectly symmetrical. Thus, the extinction ratio can be prevented from lowering in a cross mode.

The central partial junction C_5 is adjusted to a length such that the extinction ratio for the through mode has its maximum.

Thus, also in the case of this optical function element, the extinction ratio for either of the cross and through modes is much higher than in the conventional case shown in Fig. 2.

[Embodiment 1]

A 2-input/2-output directional coupler type optical function element of the present invention shown in the plane pattern diagram of Fig. 11 was manufactured. This optical function element is a modified version of the element shown in Fig. 3, in which $p_1 = p_3 = 0$ is given, that is, the incidence ends A_1 and B_1 and the emergence ends A_2 and B_2 of the optical waveguides A and B are optically connected to the curved optical waveguides D_1, D_2, D_3 and D_4, respectively, in a direct manner, without using the front- and rear-stage partial junctions.

In Fig. 11, the length of the junction C_0 is 8.0 mm, the distance G between the optical waveguides A and B is 3.5 μm, the distances G_0 and G_1 between the through port E_3 and the cross port E_4 and between the incidence ports E_1 and E_2 are both 250 μm, the curvature radius R_1 of the curved optical waveguides D_1 and D_2 and the curvature radius R_2 of the curved optical waveguides D_3 and D_4 are both 30 mm, and the path width W is 7 μm.

Gaps g_1 and g_2, g_3 and g_4, g_5 and g_6, and g_7 and g_8 with a length of several micrometers are formed between the incidence-side lead section C_1 and the front-stage partial junction C_4 with electrode, between the partial junction C_4 and the central partial junction C_5, between the partial junction C_5 and the rear-stage partial junction C_6 with electrode, and between the partial junction C_6 and the emergence-side lead section C_2, respectively. These gaps are provided lest an electrical signal introduced into each electrode influence other electrodes.

The length $p_2 \times L$ of the central partial junction C_5 is 540 μm (p_2 = 0.0675), and those of the front-stage partial junction C_4 with electrode and the rear-stage partial junction C_6 with electrode are both 3.73 mm.

The front- and rear-stage partial junctions C_4 and C_6 with electrode and the central partial junction C_5 of the junction C_0 are arranged as shown in Figs. 12 and 13, which are sectional views taken along lines XII-XII and XIII-XIII, respectively, of Fig. 11.

More specifically, a substrate 2 of n^+GaAs, a buffer layer of n^+GaAlAs with a thickness of 0.5 μm, a lower cladding layer 4 of n^+GaAlAs with a thickness of 3.0 μm, and a core layer 5 of n^-GaAs with a thickness of 1.0 μm are stacked in layers on a lower electrode 1 of AuGeNi/Au, in the order named, by the MOCVD method. Further, a cladding 6a of n^-GaAlAs, a cladding 6b of p^-GaAlAs, and a cap 6c of p^+GaAs are successively stacked in layers on the core layer 5 by the MOCVD method, thus constituting an upper cladding layer 6. The top of the cladding layer 6 is coated with an insulating film 7, such as an SiO_2 film. Thus, the two optical waveguides A and B with the path width W are formed ridge-shaped with the distance G between them.

At the regions where the electrodes F_1, F_2, F_3 and F_4 are to be mounted, as shown in Fig. 12, part of the insulating film 7 is removed to form a slit-shaped window 7a. Ti/Pt/Au is, for example, deposited on the top face of the cap 6c through the window 7a, thus forming the electrodes F_3 and F_4.

In Fig. 13, the lead f_2 for connecting the electrodes F_1 and F_4 is formed on the insulating film 7.

In the optical waveguides A and B formed in this manner, the interface between the claddings 6a and 6b constitutes a pn-junction interface 6d. If specific electrical signals are introduced from the electrodes F_1, F_2, F_3 and F_4, therefore, an electrooptical effect, plasma effect, band filling effect, etc. develop at the pn-junction interface 6d, so that the refractive index of those portions of the core layer which are situated right under the electrodes changes, and hence, the state of optical connection between the optical waveguides A and B changes.

Fig. 14 shows a theoretical characteristic curve representing the switching characteristic of this element obtained when a TE mode light beam with a wavelength of 1.3 μm is excited at the incidence port E_1, and when only the electrooptical effect is developed by applying reverse bias voltage to the electrodes.

When the element is actually driven by means of the reverse bias voltage, the extinction ratio can be estimated at 30 dB or more if the applied voltage in the cross mode is -7 V or if the applied voltage in the through mode is -15 V, in view of the conditions of a measurement system.

Fig. 15 shows the relationship between the fluctuation of the extinction ratio and the coefficient p_2 of the element observed when the coefficient p_2 is varied to change the length $p_2 \times L$ of the central partial junction C_5. In Fig. 15, circles and black squares represent the through mode and the cross mode, respectively.

As seen from Fig. 15, this element can enjoy the extinction ratio of 60 dB or more without regard to the mode, through or cross, even if p_2 or the length of the central partial junction C_5 somewhat varies.

It is evident from Fig. 15, moreover, that the coefficients p_1, p_2 and p_3 should be selected at certain values for the maximum extinction ratio of the element.

If G_0, G_1, G, R_1, R_2 and W are set at the aforementioned values, for example, the extinction ratio for the cross mode inevitably lowers unless p_1 = 0 and p_3 = 0 are established. If p_2 is deviated from 0.0675, moreover, it is impossible to obtain the maximum extinction ratio, 74.29 dB, for the through mode.

[Embodiment 2]

Another 2-input/2-output directional coupler type optical function element was manufactured. This optical function element is a modified version of the element shown in Fig. 11, in which the length of the junction C_0 is 8 mm, W is 7 μm, G_0 (= G_1) is 250 μm, G is 3.5 μm, R_1 is 50 mm, R_2 is 30 mm, p_1 = 0, the length of the central partial junction C_5 is 656 μm (p_2 = 0.082), and the length of the rear-stage partial junction C_7 is 59 μm (p_3 = 0.007375). Gaps were formed between the individual partial junctions, as in the case of Embodiment 1.

Fig. 16 shows a theoretical characteristic curve representing the switching characteristic of this element obtained when a TE mode light beam with a wavelength of 1.3 μm is excited at the incidence port E_1, and when only the electrooptical effect is developed by applying reverse bias voltage to the electrodes.

When the element is actually driven by means of the reverse bias voltage, the extinction ratio can be estimated at 30 dB or more if the applied voltage in the cross mode is -7 V or if the applied voltage in the through mode is -15 V, in view of the conditions of a measurement system.

Fig. 17 shows the relationship between the fluctuation of the extinction ratio and the coefficient p_2 of

the element observed when the coefficient p_2 is varied to change the length $p_2 \times L$ of the central partial junction C_5. In Fig. 15, circles and black squares represent the through mode and the cross mode, respectively. As seen from Fig. 17, this element exhibits the extinction ratio of 60 dB or more.

In the case of this element, moreover, the extinction ratio for the cross mode is not lowered despite the different curvature radii of the incidence- and emergence-side lead sections C_1 and C_2.

[Embodiment 3]

A 1-input/2-output directional coupler type optical function element was manufactured, as shown in the plane pattern diagram of Fig. 18. This optical function element is a modified version of the element shown in Fig. 7, in which $p_3 = 0$ is given, that is, the emergence ends A_2 and B_2 of the optical waveguides A and B are optically connected to the curved optical waveguides D_3 and D_4, respectively, in a direct manner, without using the rear-stage partial junction.

In Fig. 18, the length of the junction C_0 is 7.5 mm, the distance G between the optical waveguides A and B is 3.5 µm, the distance G_0 between the respective path-width centers of the through port E_3 and the cross port E_4 is 250 µm, the curvature radius R of the curved optical waveguides D_3 and D_4, which constitute the emergence-side lead section C_2, is 30 mm, and the path width W is 7 µm. In this element, as in the case of the element of Embodiment 1, gaps g_1 and g_2, g_3 and g_4, g_5 and g_6, and g_7 and g_8 are formed between the individual partial junctions lest an electrical signal introduced into each electrode adversely affect other electrodes.

The length $p_1 \times L$ of the front-stage partial junction C_3 is 267 µm ($p_1 = 0.0356$), the length $p_2 \times L$ of the central partial junction C_5 is 540 µm ($p_2 = 0.072$), and those of the front-stage partial junction C_4 with electrode and the rear-stage partial junction C_6 with electrode are both 3.3465 mm.

The front- and rear-stage partial junctions C_4 and C_6 with electrode and the central partial junction C_5 of the junction C_0 have the same sectional configurations as the ones described in connection with the optical function element of Embodiment 1.

Fig. 19 shows a theoretical characteristic curve representing the switching characteristic of this element obtained when a TE mode light beam with a wavelength of 1.3 µm is excited at the incidence port E_0, and when only the electrooptical effect is developed by applying reverse bias voltage to the electrodes.

When the element is actually driven by means of the reverse bias voltage, the extinction ratio can be estimated at 30 dB or more if the applied voltage in the cross mode is -8.5 V or if the applied voltage in the through mode is -19 V, in view of the conditions of a measurement system.

Fig. 20 shows the relationship between the fluctuation of the extinction ratio and the coefficient p_2 of the element observed when the coefficient p_2 is varied to change the length $p_2 \times L$ of the central partial junction C_5. In Fig. 20, black spots and black squares represent the through mode and the cross mode, respectively.

As seen from Fig. 20, this element can enjoy the extinction ratio of 40 dB or more without regard to the mode, through or cross, even if p_2 or the length of the central partial junction C_5 somewhat varies.

It is evident from Fig. 20 along with Fig. 21 mentioned below, moreover, that the coefficients p_1, p_2 and p_3 should be selected at certain values for the maximum extinction ratio of the element.

Fig. 21 shows theoretical characteristic curves representing the transitions of the extinction ratio at the through port E_3 and the cross port E_4 with $p_2 = p_3 = 0$ and p_1 varied. In Fig. 21, black spots and black squares represent the extinction ratios of the through port and the cross port, respectively. As seen from these curves, the extinction ratio of the cross port is 40 dB or more when p_1 ranges from 0.032 to 0.039, and the cross port exhibits its maximum extinction ratio when the front-stage partial junction C_3 is formed having p_1 in the vicinity of 0.035616.

In the case of the element having G_0, R, G and W set at the aforementioned values, therefore, the extinction ratio for the cross mode inevitably lowers unless p_1 and p_3 are set at 0.035616 and 0, respectively.

If p_2 is deviated from 0.072, moreover, the maximum extinction ratio for the through mode cannot take the value, 63.06 dB, shown in Fig. 19. As seen from Fig. 20, however, this element exhibits the extinction ratio of at least 40 dB.

[Embodiment 4]

Another 1-input/2-output directional coupler type optical function element was manufactured. This optical function element is a modified version of the element shown in Fig. 7, in which the length of the junction C_0 is 6 mm, W is 6 µm, G_0 is 250 µm, G is 3.0 µm, R is 50 mm, the length of the front-stage partial junction C_3 is 249 µm ($p_1 = 0.0415$), the length of the central partial junction C_5 is 498 µm ($p_2 = 0.083$), and p_3 is 0. Gaps were formed between the individual partial junctions, as in the case of Embodiment 3.

Fig. 22 shows a theoretical characteristic curve representing the switching characteristic of this element obtained when a TE mode light beam with a wavelength of 1.3 µm is excited at the incidence port E_0, and when only the electrooptical effect is developed by applying reverse bias voltage to the electrodes.

When the element is actually driven by means of

the reverse bias voltage, the extinction ratio can be estimated at 30 dB or more if the applied voltage in the cross mode is -8.0 V or if the applied voltage in the through mode is -20.0 V, in view of the conditions of a measurement system.

Fig. 23 shows the relationship between the fluctuation of the extinction ratio and the coefficient p_2 of the element observed when the coefficient p_2 is varied to change the length $p_2 \times L$ of the central partial junction C_5. In Fig. 23, black spots and black squares represent the through mode and the cross mode, respectively.

The element of this embodiment can also enjoy the extinction ratio of 30 dB or more for either of the through and cross modes.

Thus, in the directional coupler type optical function element according to the present invention, the front- and rear-stage partial junctions serve to remove the asymmetry of connection between the incidence- and emergence-side lead sections of the conventional directional couplers, and prevent the extinction ratio for the cross mode from lowering. Since the central partial junction is formed having a length such that the extinction ratio for the through mode has its maximum, moreover, the through-mode extinction ratio can be also kept high. In other words, the optical function element of the invention exhibits a high extinction ratio for either of the through and cross modes.

Thus, by incorporating the element of the present invention in an optical communication system, the possibility of cross talk can be lowered, and optical signals can be transmitted with improved accuracy.

In the embodiments described above, the optical function element of the present invention is driven as an optical switch. Alternatively, however, it may be used as a polarizing splitter which simultaneously performs, for example, injection of forward current from the electrodes and application of reverse voltage, thereby separating a TE mode light beam from a TM mode light beam. Further, the element can be used as an optical modulator or wavelength division multiplexer/demultiplexer with high extinction ratio characteristics.

Claims

1. A directional coupler type optical function element comprising:

   a directional coupler including a junction of a length L having two parallel optical waveguides of equal widths formed of a material exhibiting an electrooptical effect;

   at least one optical waveguide optically connected to the incidence end of one of the optical waveguides of the junction; and

   curved or straight optical waveguides connected individually to the respective emergence ends of the two optical waveguides of the junction,

   said junction including a front-stage partial junction of a length $p_1 \times L$, a front-stage partial junction with electrode, a central partial junction of a length $p_2 \times L$, a rear-stage partial junction with electrode, and a rear-stage partial junction of a length $p_3 \times L$,

   said p_1, p_2 and p_3 being decimals or zero satisfying a relation $p_1 + p_2 + p_a < 1$ where at least one of p_1, p_2 or p_3 is not equal to zero.

2. A directional coupler type optical function element according to claim 1 where $P_2 \neq 0$.

3. A directional coupler type optical function element according to claim 1 or 2 where the front-stage partial junction with electrode is of a length $(1-p_1-p_2-p_3) \times L/2$ and the rear-stage partial junction with electrode is of the same length as the front-stage partial junction with electrode.

4. A directional coupler type optical function element according to claim 1, 2 or 3 wherein curved or straight optical waveguides are optically connected to the respective incidence ends of the two optical waveguides of said junction, thereby forming an incidence-side lead section, the curved or straight optical waveguides are optically connected to the respective emergence ends of the two optical waveguides of said junction, thereby forming an emergence-side lead section, and said p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ $(p_2 \neq 0)$.

5. A directional coupler type optical function element according to claim 4, wherein said junction is arranged so that $p_1 = p_3 = 0$ and $p_2 \neq 0$.

6. A directional coupler type optical function element according to claim 1, 2 or 3 wherein only one of the two optical waveguides of said junction is optically connected at the incidence end thereof with a straight optical waveguide, the curved or straight optical waveguides are optically connected to the respective emergence ends of the two optical waveguides of said junction, thereby forming an emergence-side lead section, and said p_1, p_2 and p_3 are decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ $(p_1, p_2 \neq 0)$.

7. A directional coupler type optical function element according to claim 6, wherein said junction is arranged so that $p_3 = 0$ and $p_1, p_2 \neq 0$.

8. A directional coupler type optical function element according to any preceding claim wherein p_1 and/or p_3 is selected so that the coupling between

the waveguides at the incidence side of the front-stage partial junction with electrode is substantially the same as that at the emergence side of the rear-stage partial junction with electrode.

9. A directional coupler type optical function element according to claim 8, wherein p_2 is selected to maximise the extinction ratio for the through mode.

10. A directional coupler type optical function element according to claim 8 or 9, wherein p_2 is selected such that the coupling between the waveguides at the central partial junction is substantially equal to the sum of said incidence side and emergence side couplings.

11. A directional coupler type optical function element comprising:

a directional coupler including a junction of a length L having two parallel optical waveguides of equal widths formed of a material exhibiting an electrooptical effect or a material capable of refractive index control by means of an electrical signal;

at least one optical waveguide optically connected to the incidence end of one of the optical waveguides of the junction; and

curved or straight optical waveguides connected individually to the respective emergence ends of the two optical waveguides of the junction,

said junction including a front-stage partial junction of a length $p_1 \times L$, a front-stage partial junction with electrode of a length $(1-p_1-p_2-p_3) \times L/2$, a central partial junction of a length $p_2 \times L$, a rear-stage partial junction with electrode of the same length as that of the front-stage partial junction with electrode, and a rear-stage partial junction of a length $p_3 \times L$,

said p_1, p_2 and p_3 being decimals or zero satisfying a relation $p_1 + p_2 + p_3 < 1$ ($p_2 \neq 0$ or p_1, $p_2 \neq 0$).

FIG. 1

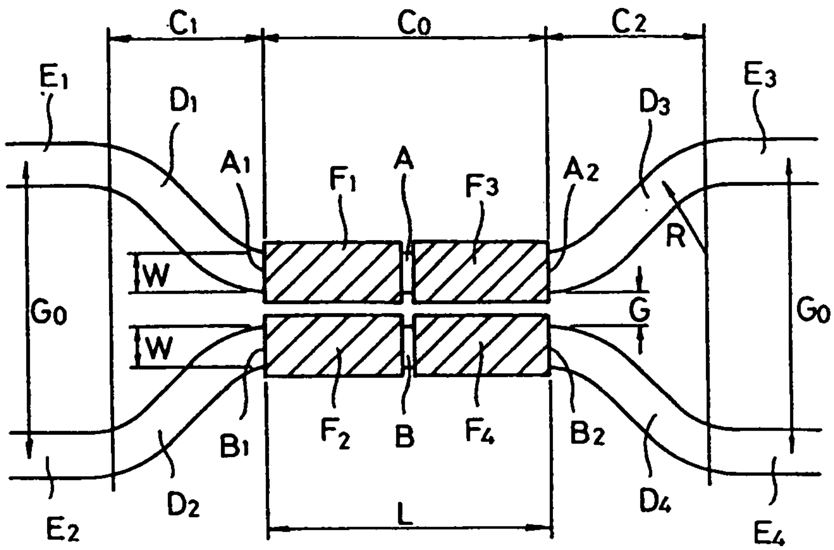

C1
C0
C2
E1
D1
A1
F1
A
F3
A2
D3
E3
R
W
G0
W
G
G0
B1
F2
B
F4
B2
D2
D4
E2
L
E4

FIG. 2

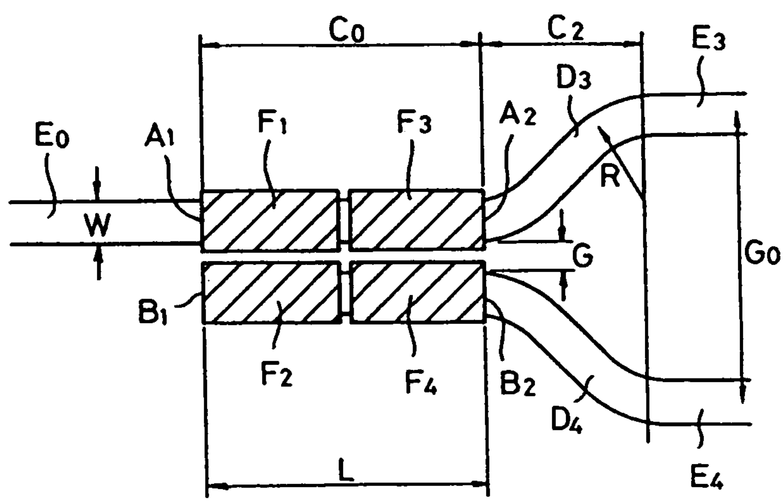
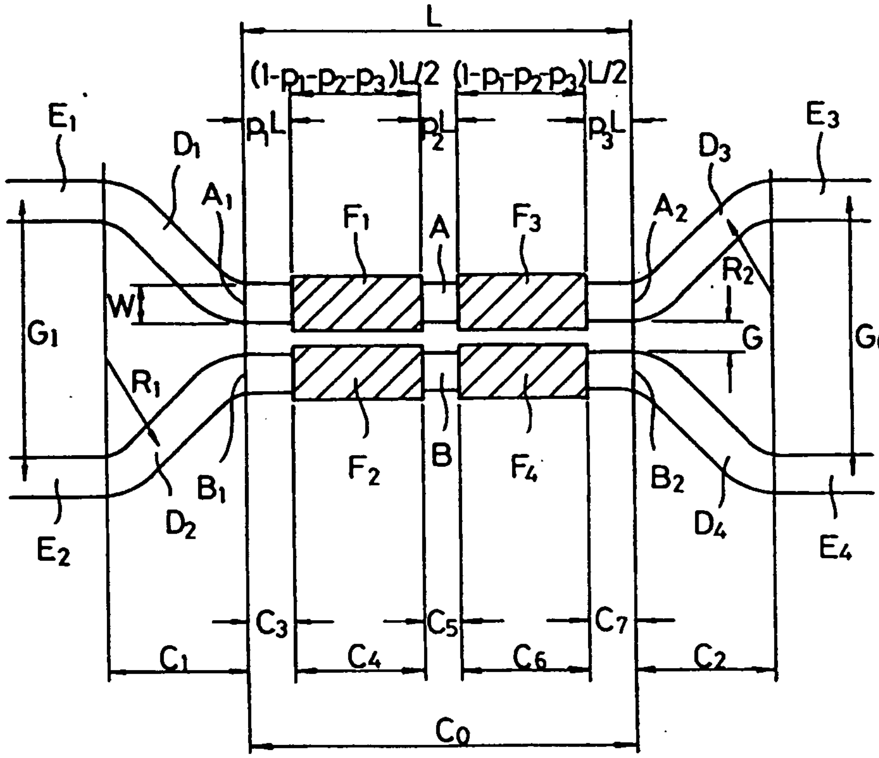

C0
C2
E3
D3
E0
A1
F1
F3
A2
R
W
G
G0
B1
F2
F4
B2
D4
L
E4

FIG. 3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(1-p1-p2-p3)L/2
(1-p1-p2-p3)L/2
p1L
p2L
p3L
E1
D1
A1
F1
A
F3
A2
D3
E3
R2
W
G1
G
G0
R1
F2
B
F4
B1
B2
D2
D4
E2
E4
C3
C5
C7
C1
C4
C6
C2
C0

FIG. 4

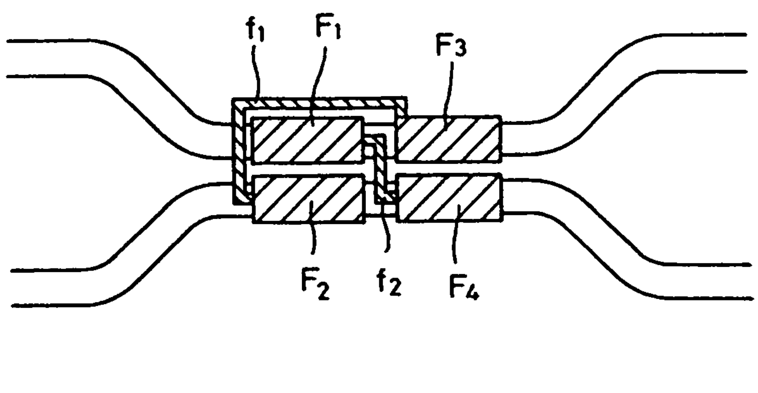

f1
F1
F3
F2
f2
F4

FIG. 5

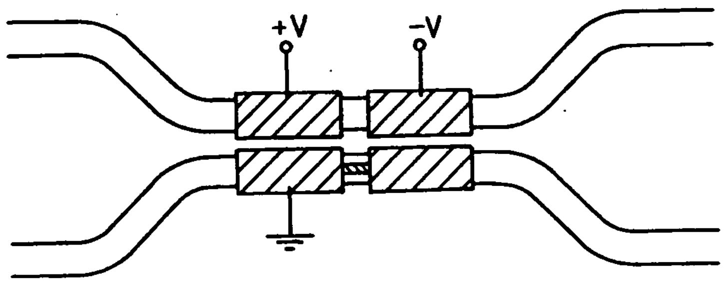


FIG. 6

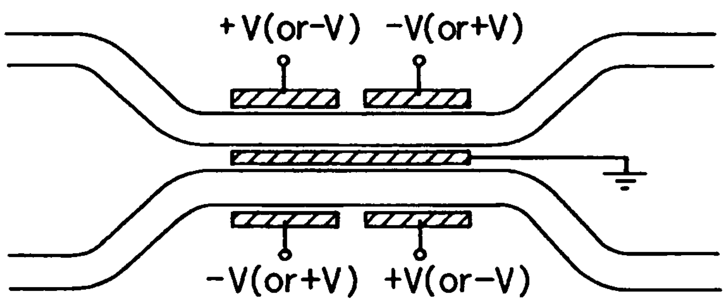
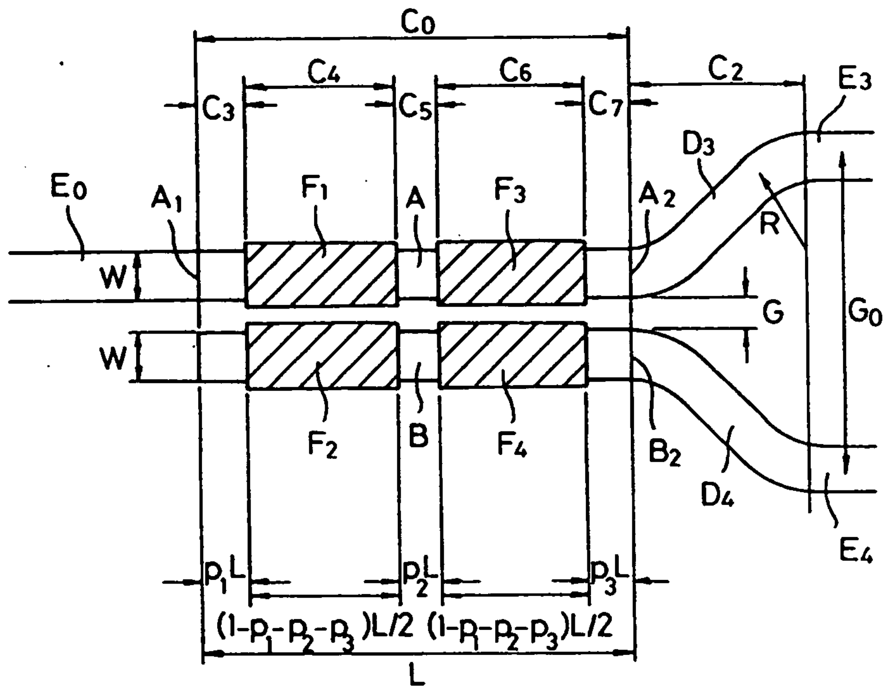


FIG. 7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C4
C6
C2
C3
C5
C7
E3
D3
E0
A1
F1
A
F3
A2
R
W
G
G0
W
F2
B
F4
B2
D4
E4
p1L
p2L
p3L
(1-p1-p2-p3)L/2
(1-p1-p2-p3)L/2
L

FIG. 8

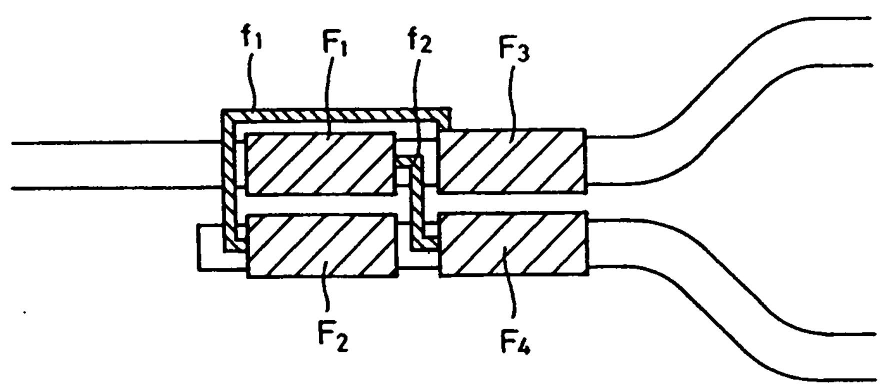

f1
F1
f2
F3
F2
F4

FIG. 9

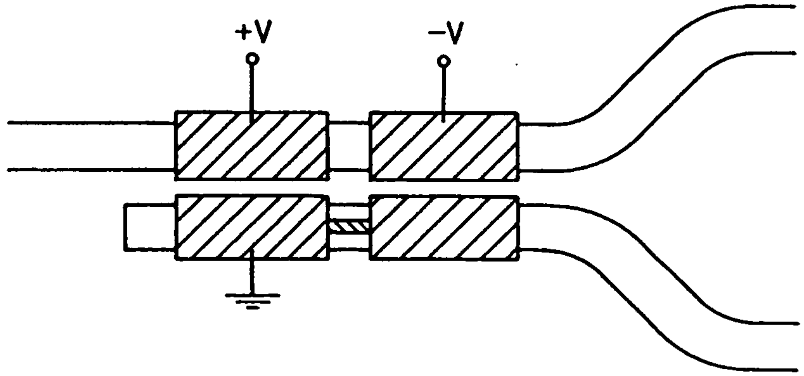


FIG. 10

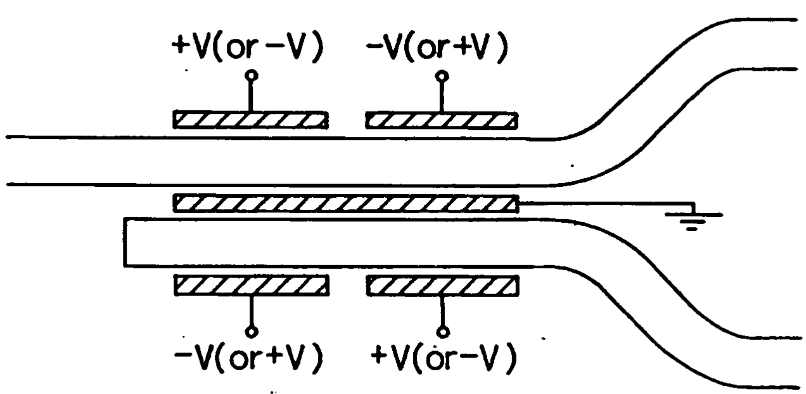
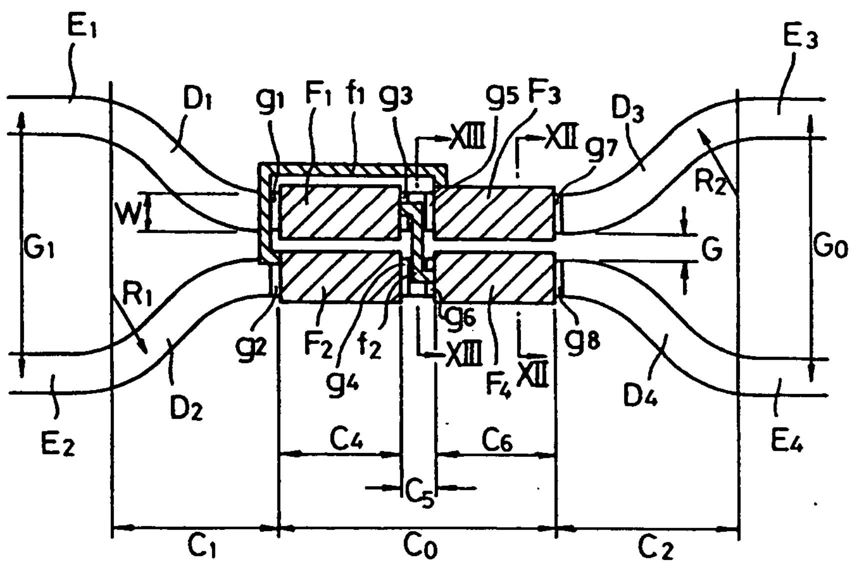


FIG. 11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E3
D1
g1
F1
f1
g3
g5
F3
D3
XIII
XII
g7
R2
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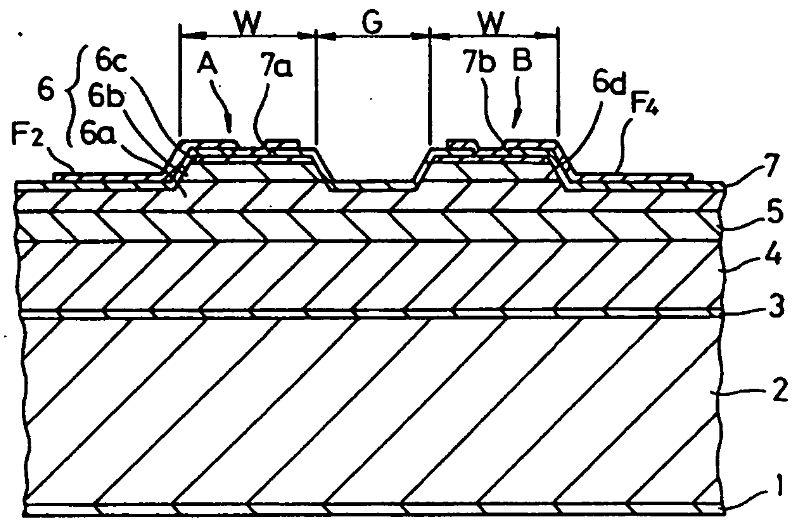
G
G1
G0
R1
g6
g2
F2
f2
XIII
g8
g4
F4
XII
D4
D2
E2
E4
C4
C6
C5
C1
C0
C2

F I G. 12


W
G
W
6
6c
6b
6a
F2
A
7a
7b
B
6d
F4
7
5
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3
2
1

F I G. 13

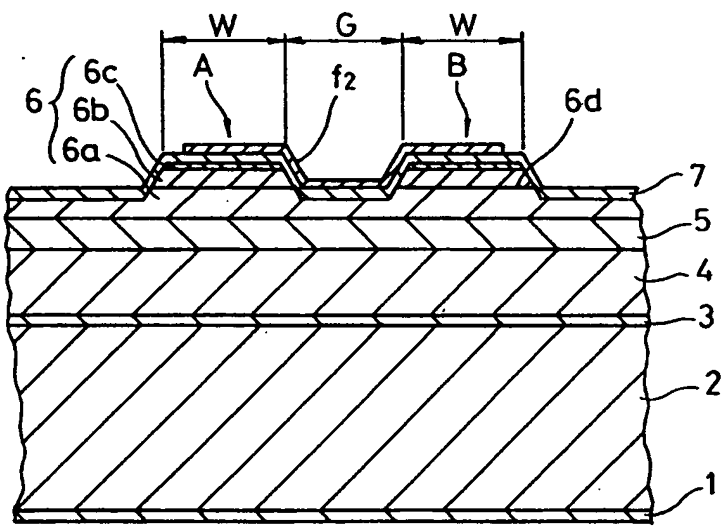

W
G
W
6
6c
6b
6a
A
f2
B
6d
7
5
4
3
2
1

FIG. 14

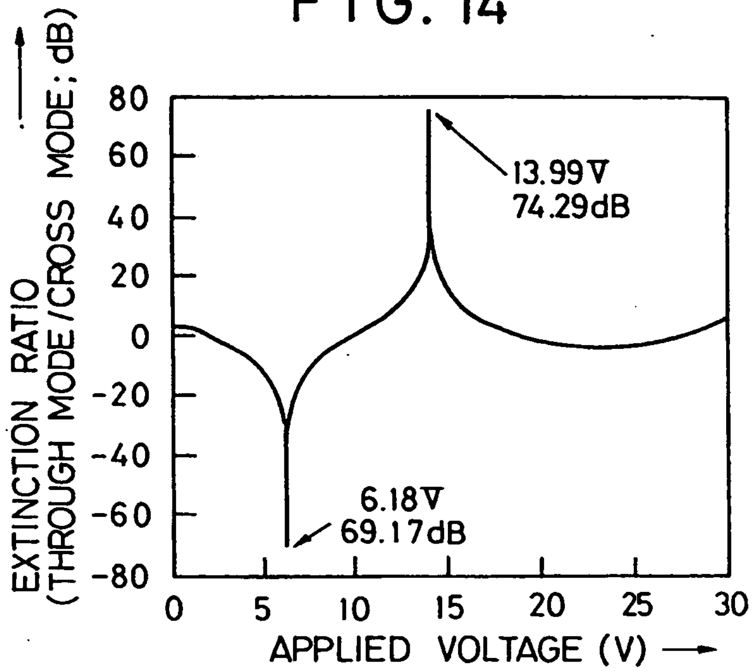
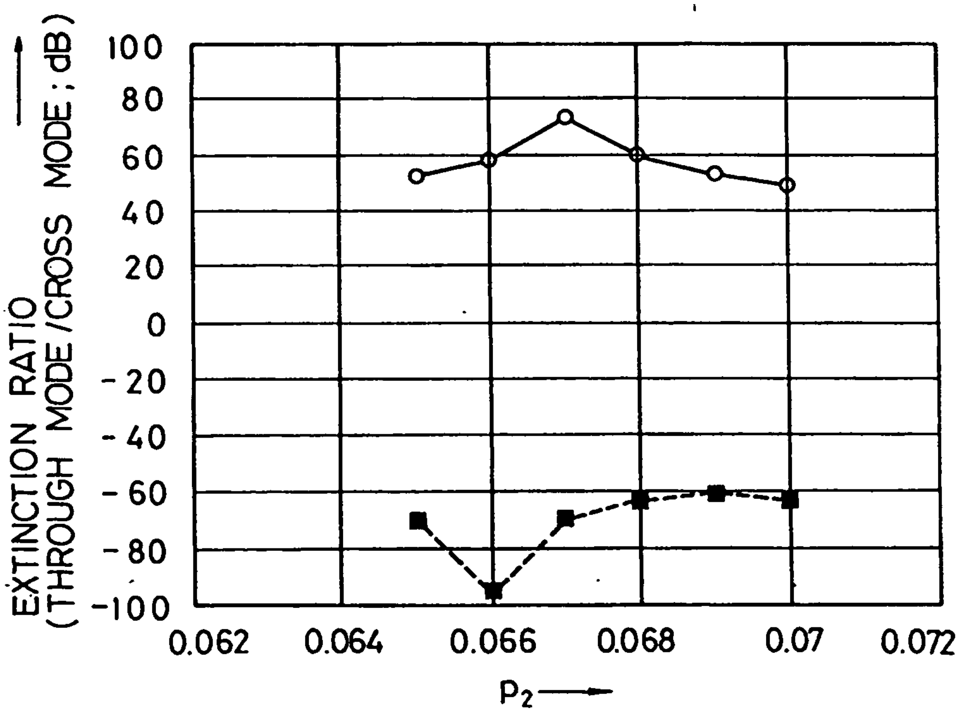
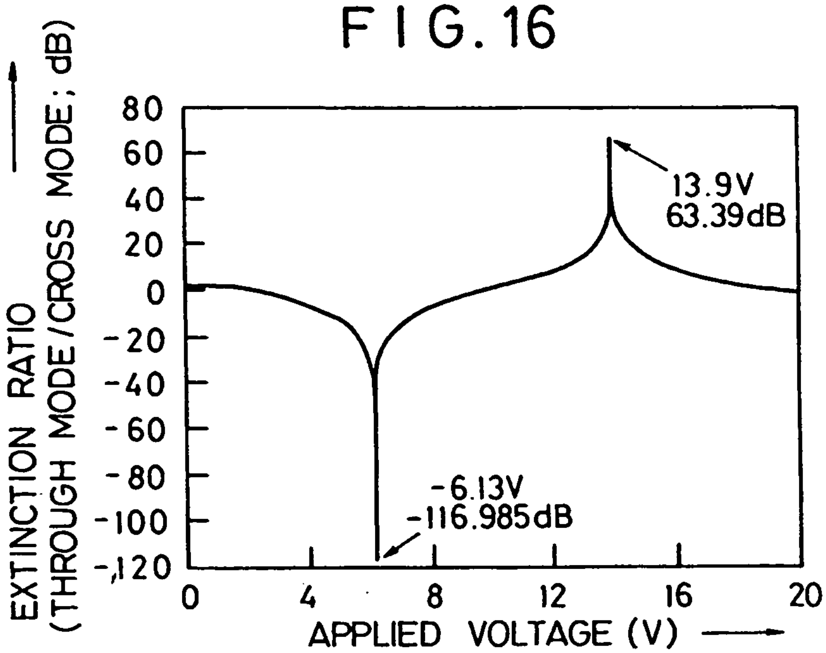

EXTINCTION RATIO
(THROUGH MODE/CROSS MODE; dB)
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
30
APPLIED VOLTAGE (V)
13.99V
74.29dB
6.18V
69.17dB

FIG. 15


EXTINCTION RATIO
(THROUGH MODE/CROSS MODE; dB)
100
80
60
40
20
0
-20
-40
-60
-80
-100
0.062
0.064
0.066
0.068
0.07
0.072
P2

F I G. 16


EXTINCTION RATIO
(THROUGH MODE/CROSS MODE; dB)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
0
4
8
12
16
20
APPLIED VOLTAGE (V)
13.9V
63.39dB
-6.13V
-116.985dB

F I G. 17

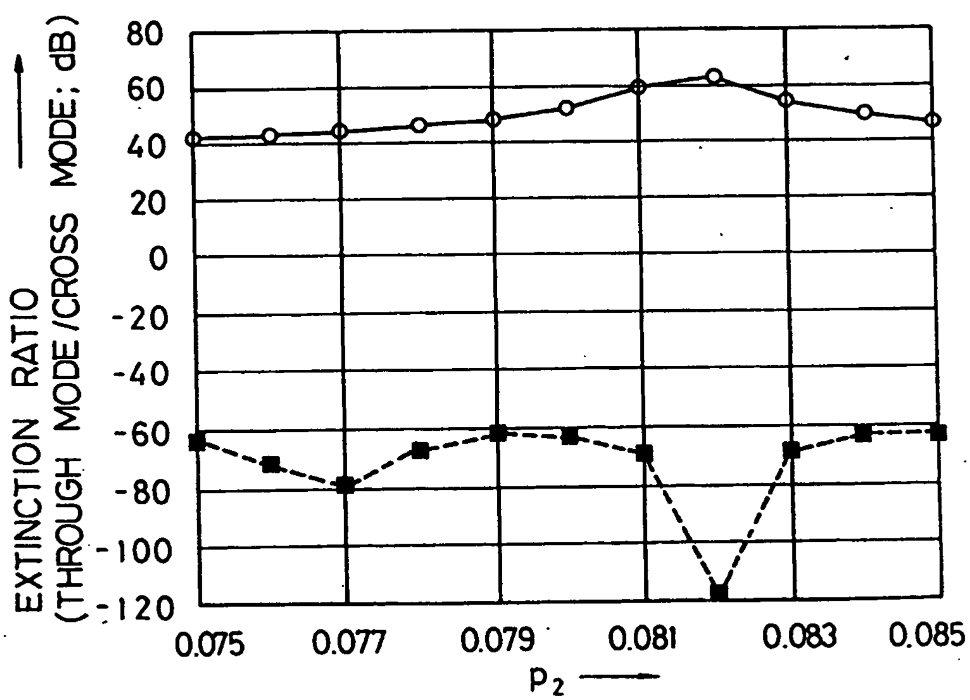
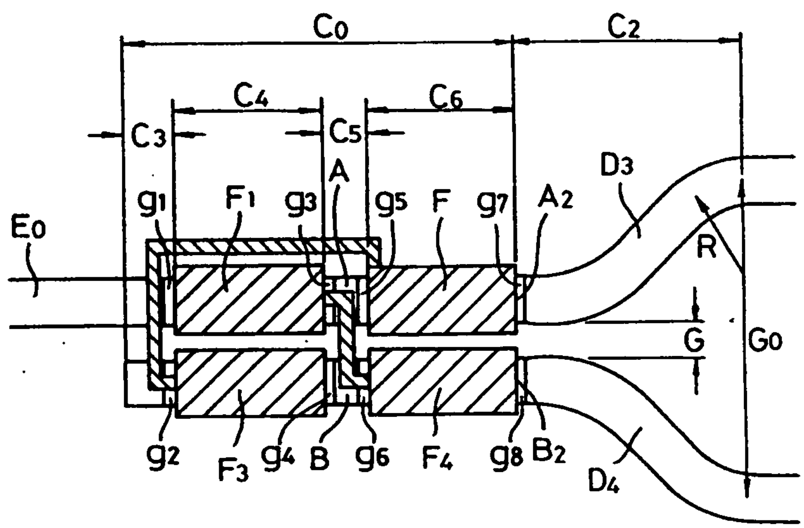
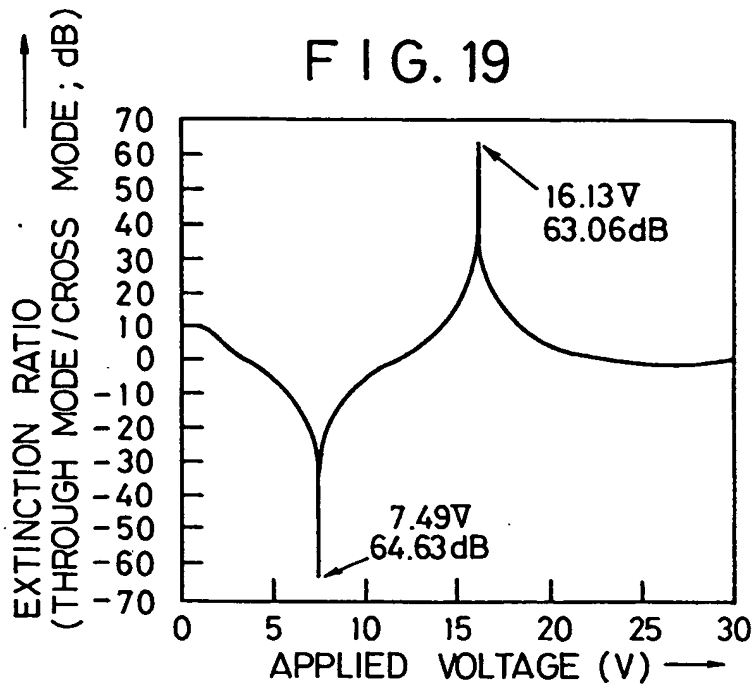

EXTINCTION RATIO
(THROUGH MODE/CROSS MODE; dB)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
0.075
0.077
0.079
0.081
0.083
0.085
p_2

FIG. 18



C0
C2
C4
C6
C3
C5
A
D3
g1
F1
g3
g5
F
g7
A2
E0
R
G
G0
g2
F3
g4
B
g6
F4
g8
B2
D4

F I G. 19


EXTINCTION RATIO
(THROUGH MODE/CROSS MODE ; dB)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
16.13V
63.06dB
7.49V
64.63dB
0
5
10
15
20
25
30
APPLIED VOLTAGE (V)

F I G. 20

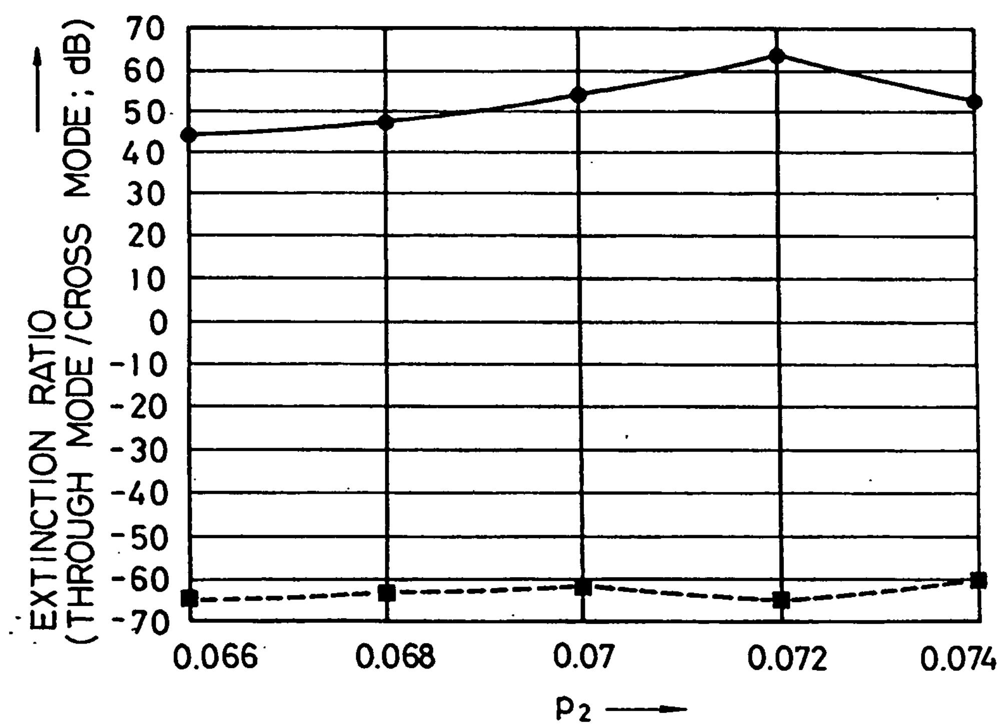

EXTINCTION RATIO
(THROUGH MODE/CROSS MODE ; dB)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
0.066
0.068
0.07
0.072
0.074
p_2

FIG. 21

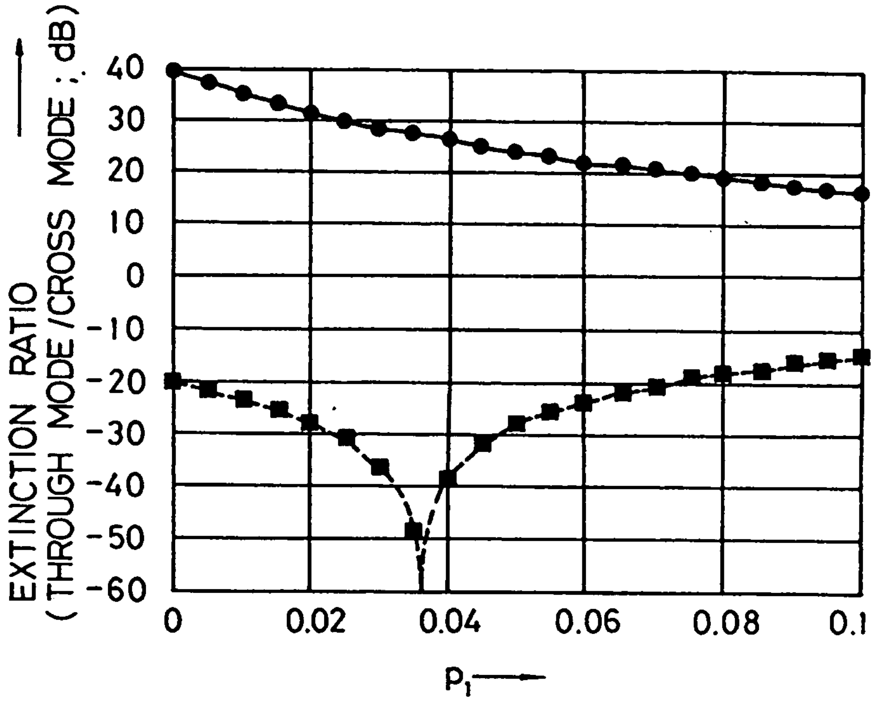

EXTINCTION RATIO
(THROUGH MODE /CROSS MODE ; dB)
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
0.02
0.04
0.06
0.08
0.1
p_1

FIG. 22

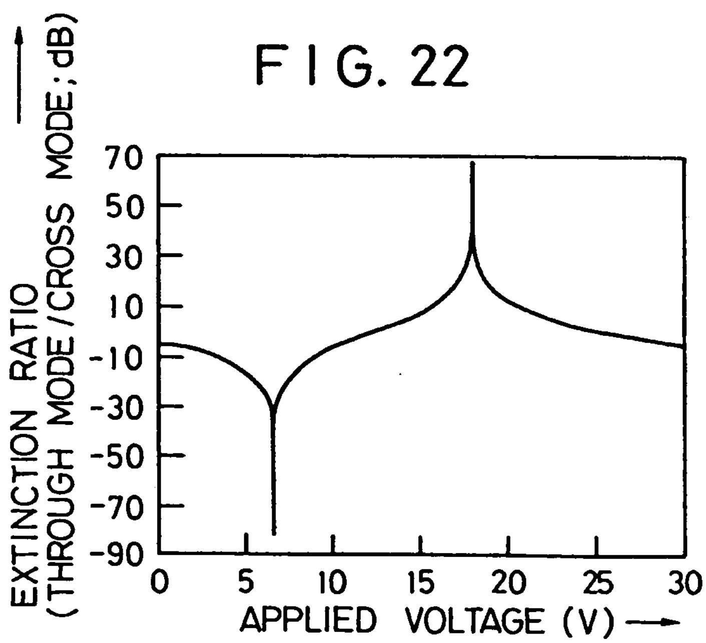
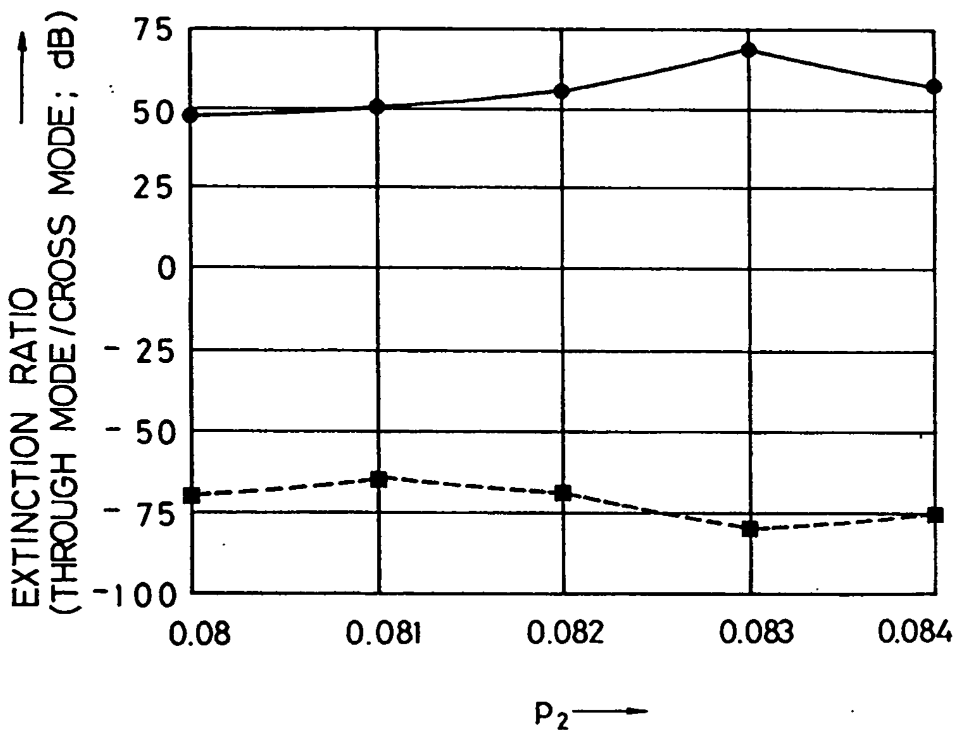

EXTINCTION RATIO
(THROUGH MODE /CROSS MODE; dB)
70
50
30
10
-10
-30
-50
-70
-90
0
5
10
15
20
25
30
APPLIED VOLTAGE (V)

FIG. 23


EXTINCTION RATIO
(THROUGH MODE/CROSS MODE; dB)
75
50
25
0
-25
-50
-75
-100
0.08
0.081
0.082
0.083
0.084
P2